Autopsy Report for TSDR169
Technical Note TD-01-063

The purpose of this report is to record the work done to determine the cause of the in-tunnel failure in TSDR169.

Technical Division's approach to this autopsy was to collectively decide how best to proceed, but also to name someone as the main contact point for this effort. That person was Tom Nicol. We also worked to systematically record the following:
1. What it is that we wanted to do;
2. What we actually did;
3. The results of what we did (this step would also include taking digital pictures).

This process would be reiterated until we came to a conclusion.

We initially envisioned making use of our "Experiment Forms" to define the work and record its outcome. It is recognized, however, that any format would be workable, as long as the content is complete.

Conclusions:

No primary conclusions have yet been drawn. There have been secondary conclusions made, which are outlined here:

1. The soft solder joint in the quench stopper bar was the primary failure point. The secondary failure point was at the flex hose around the safety lead.

2. The upgrade with a recooler had nothing to do with this failure. Upon disassembly of the failed spool, it was confirmed that there was no connection between the work done during the upgrade with a recooler and the failure in the quench stopper bar.

3. The lack of a rivet in the failed joint had nothing to do with this failure. It is believed that the presence of a rivet would not have prevented this failure.

What we know:

a) Background on the event:

The failure occurred in the Tevatron during the late shift on July 8, 2001. This appears to be the first bypass event seen by TSDR169 at its new location, and after the recooler was installed. It occurred ~25 hours into store #567 (store #567 officially began at 1930 hours on July 7; the failure appears to have occurred at 2100 hours on July 8).

The MCR e-log that records the initial event can be found at:

http://www-bd.fnal.gov/cgi-mcr/elog.pl?nb=2001&action=view&page=514

Beam's Division also issued a report recording what took place right before, and during, the incident. It is attached to this report as Attachment I.

b) Background on the spool:

TSD169 was completed in March of 1982. It was in the Tevatron at lattice location D27-1A for an extended period of time giving no trouble. It was removed from D27 around March 2000 in order to put a so-called "recooled" spool at that location. TSD169 itself then became available to be retrofitted with a recooler, which was done during April-July 2000. In November 2000 TSDR169 was installed at F47-1A.

Here is a statement (in italics) from an e-mail from Jerry Annala to Ray Hanft on 13-Aug-2001:

> *TSD169 was an original installation at D27. I found records of 5 significant quenches where the safety leads had to bypass substantial current. I believe that all of these quenches were during high energy testing.*
>
> *12/3/93 - D28L quenched at 4333 amps.*
> *10/13/95 - D28L quenched at 4440 amps.*
> *10/14/95 - D28L quenched at 4484 amps.*
> *10/17/95 - D28L quenched at 4320 amps**
> *10/19/99 - D26L quenched at 4344 amps.*
>
> ** the quench on 10/17/95 identified a weak magnet at D27-2 which is the first magnet downstream of the TSD169. The interesting thing about this quench is that the adjacent cell (D26L) quenched 0.7 seconds after the original quench. The fact that the safety lead "began to fail" at 0.7 seconds during the quench at F48 is coincidence I believe. The cell voltage during the quench on 10/17/95 looked normal before the quench spread to the adjacent cell. I will have our experts look at this quench to make sure they agree. TSD169 was removed in March of 2000 to install a recooler at D27.*
>
> *The quench that resulted in the failure at F47 was the first quench after the recooler was installed.*
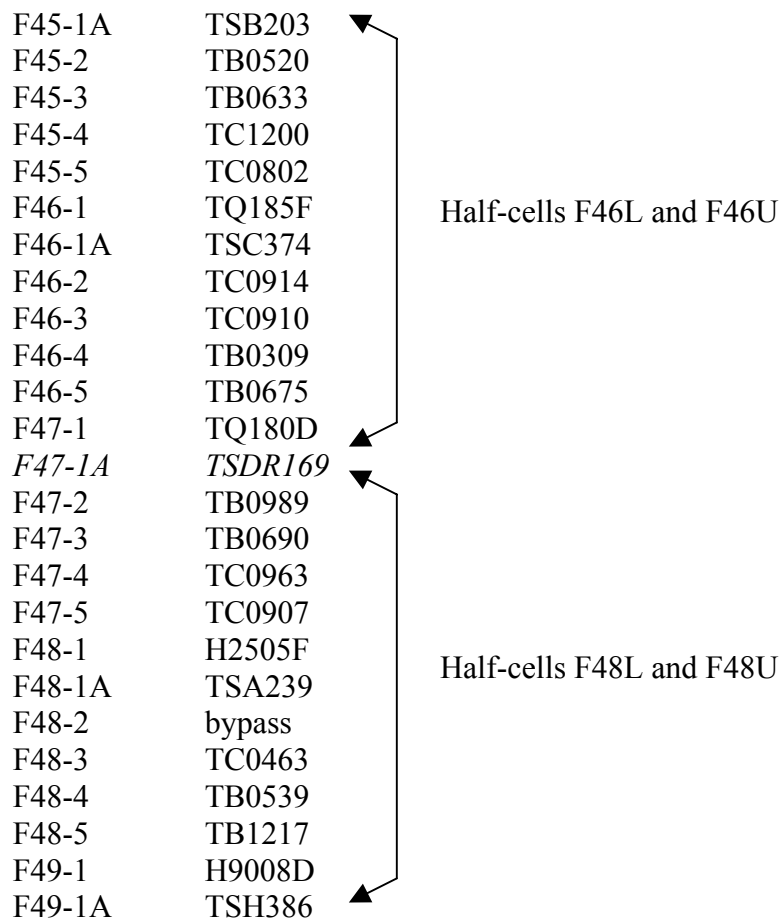>
> *When a cell quenches, the cell on the other bunch always quenches within a couple hundred milliseconds after the heaters fire (When D28L quenches, D28U always follows).*

c) Background of the tunnel environment:

The following list of devices was taken from FAMIS on 20-Aug-2001. It is thought to have been the configuration of the cells when the event occurred on 8-Jul-2001:

Note: between TSB203 and TSDR169 there are two half-cells (half the devices are on one half-cell, and half the devices are on the other half-cell - current flows in opposite directions in each half-cell). The pattern follows for the devices between TSDR169 and TSH386. The difference in voltage between two half-cells (i.e. between the two lower or the two upper, not between a lower and an upper) determines if there is a quench in one of the half-cells.

In an e-mail from Jerry Annala to Ray Hanft on 23-Aug-2001 Jerry states "*the data we are able to archive from a quench event is limited to 6 seconds of data. We always capture 1 second prior to the quench and 5 seconds after. This means that in our data archives the ring current is 2800 amps at the end of the buffers. We are blind to what happens after that time. However, the first .7 seconds of the quench that destroyed this device indicates that things were behaving normally to that point.*"

F45-1A	TSB203	
F45-2	TB0520	
F45-3	TB0633	
F45-4	TC1200	
F45-5	TC0802	
F46-1	TQ185F	Half-cells F46L and F46U
F46-1A	TSC374	
F46-2	TC0914	
F46-3	TC0910	
F46-4	TB0309	
F46-5	TB0675	
F47-1	TQ180D	
F47-1A	*TSDR169*	
F47-2	TB0989	
F47-3	TB0690	
F47-4	TC0963	
F47-5	TC0907	
F48-1	H2505F	Half-cells F48L and F48U
F48-1A	TSA239	
F48-2	bypass	
F48-3	TC0463	
F48-4	TB0539	
F48-5	TB1217	
F49-1	H9008D	
F49-1A	TSH386	

It was noted that the spool which had water put into it (TSHH373) in Feb-2001 was installed at F49-1A. Although this may seem close to F47-1A, there were 12 devices between these two spools, and it is believed that no water penetrated that far.

Paths of the investigation:

a) What's up with the surface of the failed conductor?

The smooth, curved surface of the failed lead (see picture P0006473.jpg) was a point of interest. The initial group of people looking at it did not know how that surface could be so smooth after such a catastrophic failure. It was proposed that this could either be a joint or a defect/crack in the conductor.

Two welders (Mike Reynolds and Roger Hiller) were invited to look at the failed spool and offer any insight into the interesting surface. They both stated that the smooth surface could likely be the result of the direction that the current was flowing at the time of the failure. They said that if the current was flowing into the conductor, then that smooth, rounded surface could be created. Gregg Kobliska later confirmed this as well.

Jerry Annala confirmed the current was flowing out of the spool, and into the smoothed copper (see figure 1 of Attachment I). *This leads us to believe that the smooth surface of the copper was due to a natural cause, and not a defect in the copper.*

b) The point of failure being the joint at the center of the section blown away:

It is quite possible that the failure began about in the center of the section that was blown away (see picture P0006472.jpg). The joint was about in the center of the section that had been blown apart, and so it is likely that the failure started at this joint.

The joint is a soft solder joint between two slotted pieces of copper (124638 and 124995). The original traveler (March 1982) makes this joint at step 24:

> INSTALL SAFETY LEAD ASSEMBLY
> a. Mount safety lead coils at D.S. end of 1/0 box.
> b. Connect leads to quench stopper.
> c. Align & tack weld safety lead assy to 1/0 box.
> d. Insulate connection between quench stopper & safety lead.
>
> ASSEMBLED BY [Bob + Chris]   DATE [3-4, 3-5]
> WELDED BY [left blank]   DATE [left blank]

The traveler makes no mention of the solder used. It is thought that the solder is 60/40.

It was recalled (and confirmed on a safety lead assembly pulled from stock) that at some point during the fabrication run of spools there was an engineering change to add a rivet to this soft solder joint. Denny Gaw, Tom Nicol, Dean Sorensen and Tom Wokas could not recall why this rivet was installed. The recollection of Dan Smith was that this was a precautionary measure to

add strength to the joint, in the event that the solder failed. It was noticed that this magnet had no provision for riveting the quench stopper bar to the safety lead.

The ECO for this change was #758, dated 4-13-82. The actions assigned on that ECO were to rework existing stock and issue changes to existing orders. The dates confirm that this change was enacted after TSD169 was built.

We agreed that the addition of a rivet at that joint was not likely to hold the joint together in the event that the solder failed. It seems more plausible that the rivet was added as a fabrication aide, to keep the joint in position while soldering. *It was agreed that the lack of a rivet was not an issue during the failure of TSDR169.*

c) The solder:

Our attention then turned to the solder. Questions were raised such as "what solder was used?", "what temperature does the solder melt at?", "what temperature is the joint designed to handle?".

Moyses Kuchnir was invited to come look at the failed spool and offer any insight he may have. Moyses was a central figure in the design of the quench stoppers and safety leads. Moyses produced a number of documents which he provided to us. Two are with this document as attachments, and 4 are linked to the Fermilab preprint database (available through the FNAL library web site: http://fnalpubs.fnal.gov/):

> Attachment II - Spool Piece Testing Facility
> Attachment III - Automatic Measurement of Heat Load
> Consecutive Quenches and the Safety Leads, TM-1256
> Safety Leads, TM-915
> Safety Lead Material Selection, TM-674
> Measurement of Safety Lead Heat Leak, TM-702

After some deliberation, Moyses thought the primary failure occurred at the copper joint, and the secondary failure was the safety lead (where there was a short through the flex hose that holds the safety leads; see picture P0006392.jpg).

Based on the information recorded in the Tech Memos listed above, a figure of 106 MIITS is used for the design of the safety leads (this used max current of 4.6kA and decay time of 10 seconds). If we use the same amperage, but increase the decay time to 12 seconds (which is the most recent thinking) the number increases to 127 MIITS. It is still unknown whether the safety leads were designed to handle this level of MIITage.

We are working on determining the temperature that is generated at this level of MIITage. 60/40 solder softens at 188°C. TM-674 refers to a "still safe temperature" of 180°C.

A note found by Tom Nicol (who was a designer working with Moyses on the safety leads) said the required copper area for the safety leads is 0.8 to 0.82 cm^2, and that "this is to assure

that the total heat developed is not sufficient to melt soft solder." The rod used is .490" diameter, or 1.22 cm^2, and the bar used is 5/8" x 1/4", or 1.00 cm^2.

d) Electrical considerations:

Dan Wolff was invited to come look at the failed spool and offer any insight he may have. Dan is an expert in the electrical properties of the Tevatron.

He believed that the point of failure was the soft solder joint. He said that once an arc started there was no way to stop it (with the current being ~4400amps). It kept eroding away the copper, and the inductance would increase the voltage until it would arc again. The potential needed to keep the arc going is on the order of 10's of volts, and that number would continue to increase as more copper was eroded (making a larger gap). At some point in that process he thought that it was electrically easier for the current to jump to the stainless steel box and then back into the safety lead at the second point of failure (where the hole was made in the flex hose, see picture P0006392.jpg).

He also stated the worst case voltage on the safety lead was 1000v, that the inductance was about 40 Henrys, and that 5 quenches is not a lot of quenches.

The "tear down" of the spool:

The work of tearing down the spool and looking for clues about its failure are outlined here:

7/16/01
Shipped to IB2 from tunnel due to electrical problem.
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006342.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006343.JPG

7/25/01
Removed vacuum box side plate (124312).

7/26/01
Remove shield mli.
Remove shield side plate (124381).

Found soot and shredded mli.

Removed mli from safety leads and safety lead box ass'y (125095).

Found a hole in the lower safety lead flex hose.
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006392.JPG

Found a hole blown through the d.s. 1-phase box plate (124302).
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006402.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006403.JPG

Removed the front safety leads box plate.

http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006373.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006375.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006376.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006378.JPG

7/27/01
Removed vacuum box top plate (124398).

7/30/01-8/3/01
Removed mli from shield top plate (124380).
Removed shield top plate.
Cut through the sniffer bellows between the d.s. vacuum can and beam tube.
Cut through thermal braid between sniffer and ln2 tube.
Remove vacuum vessel end plate (291332) from radial vacuum vessel extension (291330).
Cut through radial vacuum vessel extension and d.s. vacuum can (124401) flush with vacuum box.
Remove d.s. shield can mli.
Separate heat strips (125099) from between the shield can and the ln2 tube.
Remove the 2 shield end caps (291327) and the shield extensions (291328 & 291329).
Remove heat exchanger and 1-phase mli.
Cut through 2-phase outlet tube (291351) at joint with 2-phase tube.
Cut through 1-phase inlet tube (291353) and 1-phase outlet tube (291352) flush to 1-phase bellows can.
Separate heat exchanger support (291344) from 1-phase can (124395) and remove heat exchanger (258871).
Remove vacuum box end plate (124402).
Remove d.s. shield plate mli.
Remove d.s. shield end plate.

http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006437.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006439.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006450.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006454.JPG

8/6/01-8/9/01
Remove beam tube bellows (103839).
Remove d.s. 1-phase bellows cup with bellows (106998) to expose bus cables and flow restrictor (291349).
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006459.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006460.JPG

Found no evidence of shorting.
Separate 1-phase relief tube (124588), 2-phase relief tube (124584) and ln2 relief tube (124571) from vacuum box side wall (124399).
Remove vacuum box side plate.

Remove shield mli.
Remove shield side plate (124382).
Separate vacuum box bottom plate (124313) from vacuum end plate (124314).
Set magnet on roll-over stands.
Remove bottom shield plate (124566).
Remove remaining mli.
Remove the bottom plate from the safety lead box.
Remove the g-10 bar lead insulator (124981) and the safety lead cover plate (124993).
Upon opening up the safety lead box, it was discovered that the joint between the lower safety lead and quench stopper bar had blown apart

http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006472.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006473.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006475.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006482.JPG
http://tdserver1.fnal.gov/proeng/magnetphotos/Tev_Spools/TSDR169/P0006485.JPG

Failure of TSDR169 at F47 on July 8, 2001
Jerry Annala

This is an attempt to summarize the failure of the spool piece at F47 on July 8, 2001. The serial number of the spool installed at the time was TSDR169. Below is a simplified schematic of the Tevatron Lower bus around the spool piece. The cell voltage is measured on the Tevatron bus near the point where the safety leads (shown as double lines) connect to the bus. The voltage on the F46L cell is the difference in voltage V2 - V1. The voltage on the F48L cell is the difference in voltage V3 - V2. The voltage in a cell $V_c = -(L*dI_m/dt) - (I_m*R_q) = -(I_b*R_b) - (V_{scr})$. L is the inductance of the cell, I_m is the current in the magnet string, I_b is the current being bypassed through the QBS circuit, and V_{scr} is the voltage drop across the bypass SCR. R_q is the resistance of the magnets due to the quench, and R_b is the resistance of the bypass circuit including the 250 MCM bypass cables and the safety leads. Before a cell quenches, I_b is zero, the SCR stands off whatever voltage is present across the cell. After the cell quenches, nearly all of the current is bypassed from the magnets (I_m is almost zero) and V_{scr} is essentially a constant near a value of 2 volts.
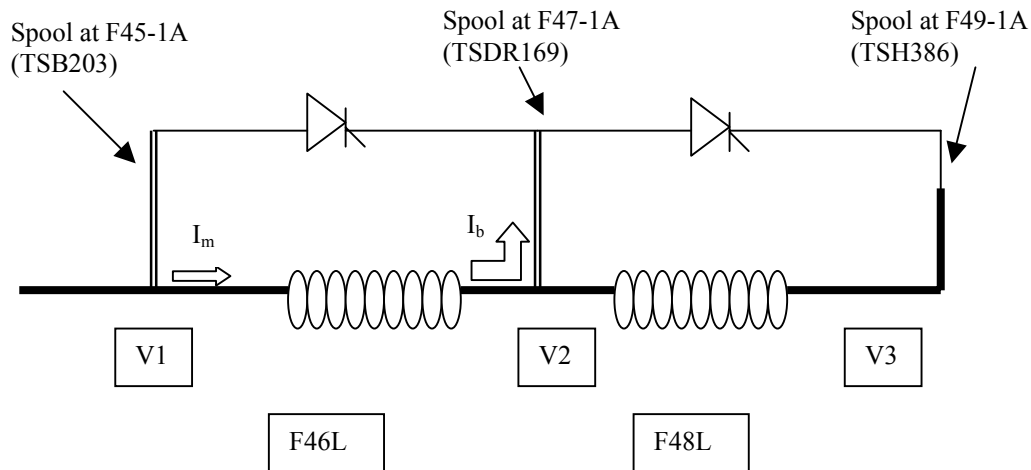

Figure 1. Simplified schematic of F46L and F48L quench protection cells.

Figures 2 and 3 below show the cell voltages for F48L and F46L cells. The quench was caused by an abort kicker prefire. The quench initially develops normally in F48L. The cell voltage signal for these two cells looks exactly as expected up to about .7 seconds. Before this time the voltage across F46L is entirely due to the $(L*dI_m/dt)$ term. By .5 seconds, almost all of the current is bypassed from the magnets in F48L and the cell voltage there is determined by $-(I_b*R_b) - (V_{scr})$. Just after .7 seconds, something happens that rapidly increases the voltage on F48L. My assumption is that the R_b term increases at the point of the damage in the safety lead at F47. By just after .9 seconds, the extra voltage in the F48L cell (which is in the F47 safety lead) is about 80 volts which is

enough to forward bias the QBS across the F46L cell. After 1 second, the cell voltage channels are saturated (above 200 Volts) and the signals are meaningless. At 1.5 seconds the channels come out of saturation.
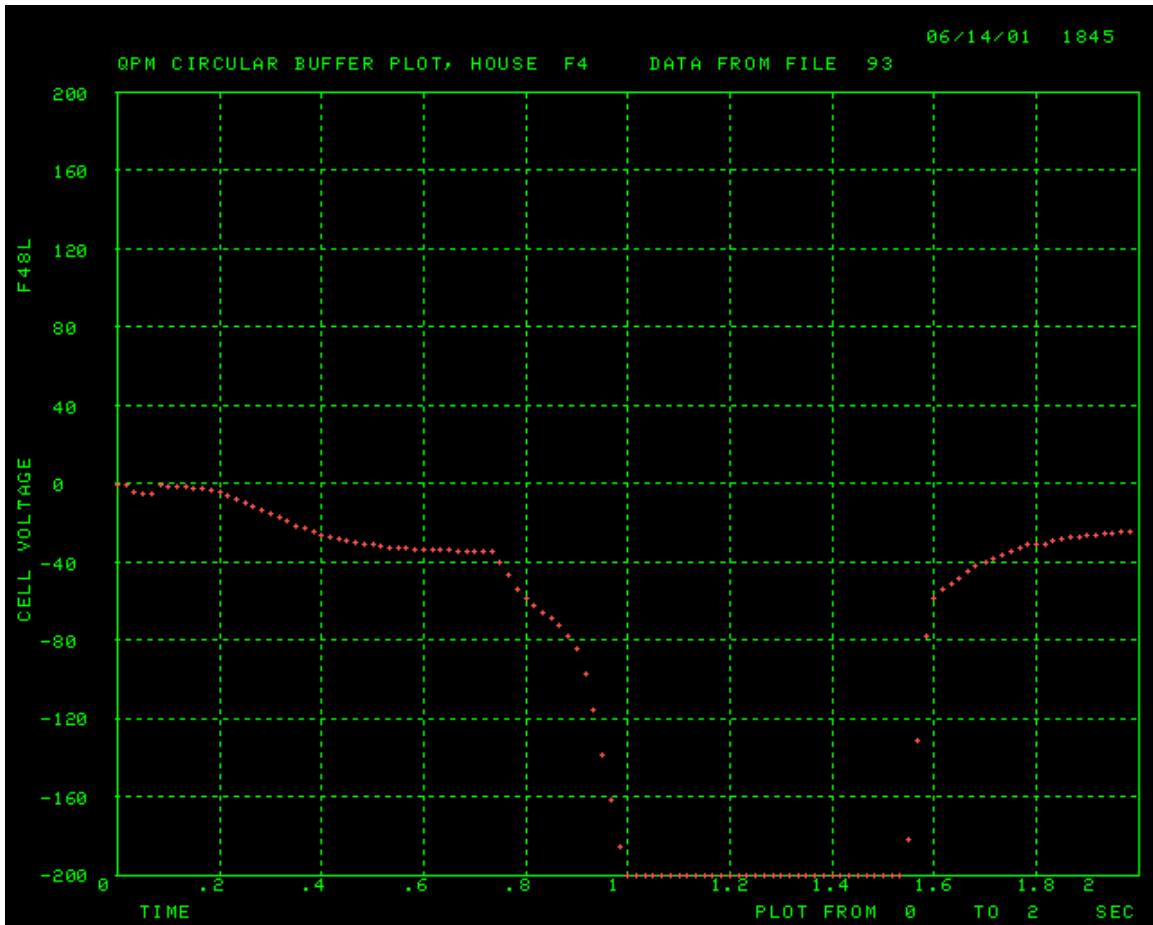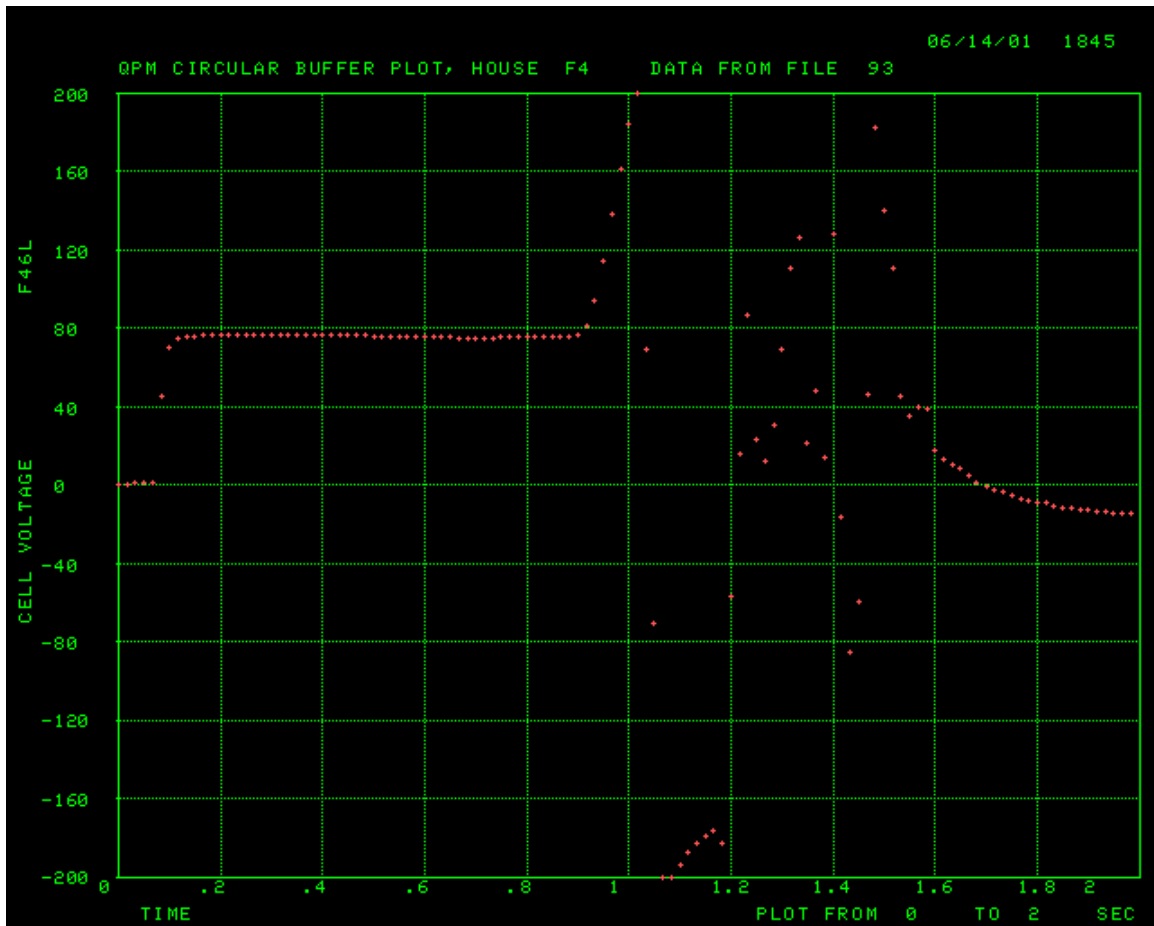

Figure 2. F48L cell voltage

Figure 3. F46L cell voltage

SPOOL PIECE TESTING FACILITY

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Introduction

"Spool Piece" is the name given to the modular component of the Energy Saver which contains the correction magnets and several other devices required by the superconductive and cryogenic nature of this synchrotron. Approximately 230 spool pieces will be built to go along with 774 dipoles and 224 quadrupoles. To this date four have been built and the plans for a production rate of five per week are being implemented.

The Spool Piece

Like the other components, the spool piece volume comprises the "beam vacuum tube", the "single-phase (1∅)" pressurized liquid helium space (where the superconducting coils, busses and leads are located), the two-phase (2∅)" boiling helium space, the liquid nitrogen-(LN₂) cooled shield and the insulating vacuum space. There are actually two insulating vacuum spaces separated by the "vacuum barrier" that compartmentalizes the insulating vacuum to lengths of one half-cell of the synchrotron (four dipoles, one quadrupole and one spool piece). Figure 1 is a schematic diagram of a spool piece. Each one of the fluid-containing volumes has a safety "vent pipe". These vent pipes are provided with cold check valves for thermoacoustic oscillation prevention and coupled to Kautzky valves[1] at room temperature (not shown in Figure 1). Every dipole cryostat has a vent pipe for the 1∅ space, for quench handling. The 2∅ and LN₂ vent pipes of the spool piece serve the whole half-cell.
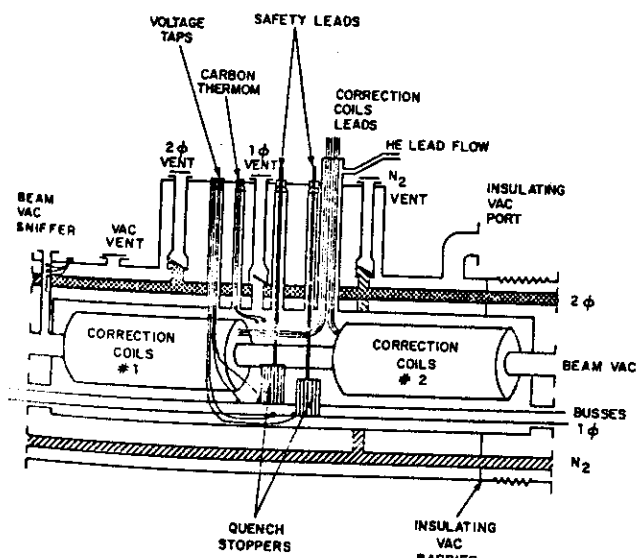

Figure 1. Spool Piece schematic diagram.

The "safety leads"[2] provide room temperature access to the superconducting busses that connect the magnets through the spool piece. Current flows through the safety leads only during the emergency shutoff of the accelerator after a quench. Connecting the safety leads to the busses are the "quench-stoppers", copper

conductors with large surface area in contact with the 1∅ helium intended to prevent the busses from going normal during an emergency shutoff. The beam vacuum sniffer is a tube connecting the beam vacuum to ultra high vacuum measuring equipment,[3] it is instrumented with heaters and a thermocouple thermometer. Other self-explanatory parts of the spool pieces are the voltage taps used by the quench protection monitor,[4] carbon resistance thermometers, vapor-cooled correction coil leads and the insulating vacuum port.

Refrigerator System

Since they contain superconducting elements, the spool pieces have to be tested filled with liquid helium. For this purpose a refrigeration system and a testing system were assembled. A scheme based on connecting several of them and cooling them simultaneously is being used to reduce the cooldown and warmup time.

The refrigeration system provides closed loop refrigeration for flowing pressurized liquid helium through a string of spools. The system was built from components used in testing magnet strings in the B-12 service buildings. The components are arranged as shown in Figure 2. The refrigeration is provided by two CTi Model 1400 refrigerators and five CTi Model 1400 compressors. The system can provide about 100 watts of cooling at 4.5°K.
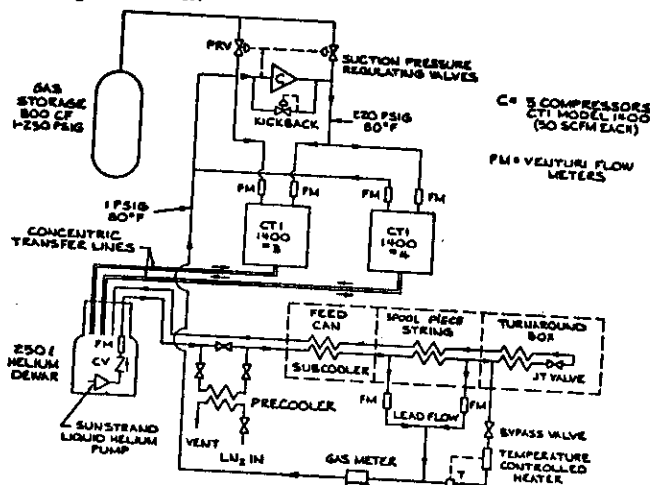

Figure 2. Main helium flow schematic.

Part of the available cooling is used by the Sunstrand centrifugal pump, which can provide 5-10 psi of pressurization and 12-25 g/sec of flow. The pump heat load is typically 30-50 watts.

In addition to the equipment shown in Figure 2, a liquid nitrogen storage dewar and distribution system, a liquid nitrogen-cooled charcoal purifier, and equipment to monitor nitrogen and water contamination were installed. During the initial cleanup of the system, extensive use was made of a refrigerated dryer borrowed from the Central Helium Liquefier to remove the water from the system.

When using the system for cooldown or static heat load measurements, flow is taken from #3 refrigerator only. Whenever the pump is circulating liquid through the magnet string, #4 refrigerator runs as a relique-

fier with its expanders not running. This mode of running has the advantage of producing stability and the lowest temperature at the magnet string due to the parallel flow paths for gas exiting the dewar.

The by-pass valve on the turnaround box is used to obtain one-pass gas flow for cooldown, static heat load measurements and warmup.

Testing Program

As far as cooling conditions, three kinds of tests are performed: room temperature tests prior to connection, static heat load measurements with just LN_2 and cold He gas flowing through, and performance tests under near-operating conditions. The sets of tests to be performed have not yet been standardized, but so far we have carried out the room temperature tests as an extension of the quality control that is carried out during manufacture. Beside visual inspection, low voltage isolation and continuity checks, high voltage isolation tests are carried out. They are again repeated during cooldown with helium gas near 80K in the 1Ø volume and finally just prior to the performance tests.

For the static heat load measurements resistance thermometers are installed between them, in the single-phase helium flow path. Cold helium gas flows through the single-phase volumes of this train of spool pieces, entering the first one at ~10K and leaving the last one at ~25K. This gas, after warmed up to room temperature, flows through a gas meter and returns to the compressor of the refrigerator. A microprocessor-based data acquisition system records the time and the readings of all relevant thermometers, pressure gauges and the gas meter at set time intervals. When the refrigerator plus the spool pieces reach a steady state condition these data are used for estimating the heat load between thermometers by the enthalpy increase in the helium flowing past these thermometers.

In the third cooldown of the facility (second SPTF test) one Energy Saver dipole was cooled along with two spool pieces. Table I summarizes the heat load data obtained at five different steady state conditions regarding the helium flow through the correction element leads or additional power in the dipole quench heater.

Table I

Heat Loads Into Liquid Helium Region

Steady State Point	1st Spool Piece	E.S. Dipole	2nd Spool Piece	Lead Flow	Electrical Power introduced into E.S. Dipole Heater
1	18.5W	9.7W	17.7W	0 scfh	0 W
2	18.7	14.6	17.7	0	5.0
3	17.7	18.4	18.0	0	10.0
4	10.7	9.3	10.6	22.5	0
5	14.2	9.0	13.1	3.0	0

For the performance tests the helium flows, as in an Energy Saver cryoloop: pressurized liquid helium flows through the 1Ø volumes; i.e., by the superconducting elements to the "turnaround box" where it is expanded through a Joule-Thompson valve and returned through the 2Ø volumes as boiling mixture to the refrigerator. The lack of a beam and a separate vacuum in the beam tube are the only things that keep this condition from being exactly the operating condition. So far the performance tests have been the testing of

3326

the correction elements and the safety leads.

In general each spool piece contains two correction packages. Each package has three superconducting correction elements.[5] The test procedure for the correction coils determines the stability of individually powered elements and the stability of all three elements in a package operating at maximum current (50A).

The test equipment consists of three 100A supplies connected to ramp generators. Although the power supplies to be used in the Energy Saver are limited to 50A, the higher current of the test supplies allows a more extensive investigation of the properties of the coils. The test sequence begins by ramping each of the six magnetic elements to 100A (about half the short sample limit). Defects such as resistive splices or poorly impregnated coils will result in excessive quenching below 100A. A good coil will usually reach 100A without quenching. The package is then tested for stability when all the elements of that package are powered. The three elements are tested at the three possible relative polarities and are stepped in current until the onset of quenching. In particular, the elements are ramped one after the other to the given current and then successively ramped down. The polarity of one element is reversed and the sequence repeated until all relative polarities have been tried. The packages tested so far operate stably to 60 or 70A.

The safety leads and quench stoppers have been tested by splicing the busses together at one end and driving a current pulse of 5kA with a 12 sec decay time constant while monitoring voltage taps on the busses near the quench stopper. This test is being further developed, but so far the results are consistent with proper quench stopper operation. The cooldown time for the safety lead after one of these pulses is rather slow (~hours) for the rate with which the quench protection monitor[4] is being tested, but the safety leads can take two or three of these pulses without cooling off.

So far this facility has been operated three times for adjustments on the refrigerator mode of operation and the development of these tests.

An important part of the operation has been the training of the technicians that are going to be running the facility. Work now is concentrating on programming the computer that controls the data acquisition system and does the data reduction.

References

1. H.Kautzky specially designed these valves for high CV and thermal shock.

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AUTOMATIC MEASUREMENTS OF HEAT LOAD

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INTRODUCTION

The components of a large system of superconducting magnets, such as the Fermilab Energy Saver are usually refrigerated by flowing helium. The heat load into the helium temperature region of a component can be obtained in a straightforward way by measuring the pressure, the mass flow rate and the increase in the temperature of the cold helium gas flowing through it. The heat load is then the product of the corresponding increase in enthalpy by the mass flow rate. This method[1] is used to determine heat loads of individual Energy Saver components, dipole magnets, quadrupole magnets and "spool pieces" which are cryostats containing the higher order correction magnets and most of the accessories of a cryogenic nature.

PROCEDURE

The preparation for the tests involves connecting together one to six components with special inserts between them, a turn-around-box at one extremity and a refrigeration system at the other. This forms a cryogenic circuit similar to an Energy Saver cryoloop. The special inserts introduce two thermometers in the single phase helium flow stream, one before and one after the junction formed by consecutive components. After leak checking, the train of components is cooled by starting the flow of liquid nitrogen through the shields and cold helium gas through the single phase helium path.

M. Kuchnir

The two-phase (boiling) helium path used in the operating mode[2] is kept valved-off. The gas exiting from the turn-around-box is warmed to room temperature and returned through a positive displacement-type gas meter to the refrigerator compressors. Cooling proceeds until the helium gas enters the train at ~ 5.5 K, at which time stability is achieved by electronically controlling the inlet temperature, manually adjusting the refrigerator for a steady mass flow rate and waiting for equilibrium. Figure 1 presents a diagram of a typical train of six spool pieces with the sensor location indicated. For heat load measurements, dipole and quadrupole magnets can replace spool pieces in the train.

DATA ACQUISITION SYSTEM

The data acquisition system, with a digital multimeter[a] and a scanner[b] uses components available in the microprocessor market. The microcomputer[c] has an S-100 bus structure with a 64 K memory, a TU-ART interface, a 100 000-day clock[d], two 5-inch disk drivers and a pulse counter. A graphics terminal[e], a printer[f], plus a few homemade electronic modules complete the system. Data transmission follows the RS232 standard.

The pressure transducers used are based on integrated circuit technology[g]. Two precautions make these inexpensive units quite acceptable: the use of those which measure gauge pressure (helium diffusion spoils the reference pressure in absolute-pressure gauges); and the design of special packaging. We have a transducer installed in the insulating vacuum of the turn-around box which provides the barometric pressure for the calculation of absolute pressure. A Baratron[h] has been used to check transducer
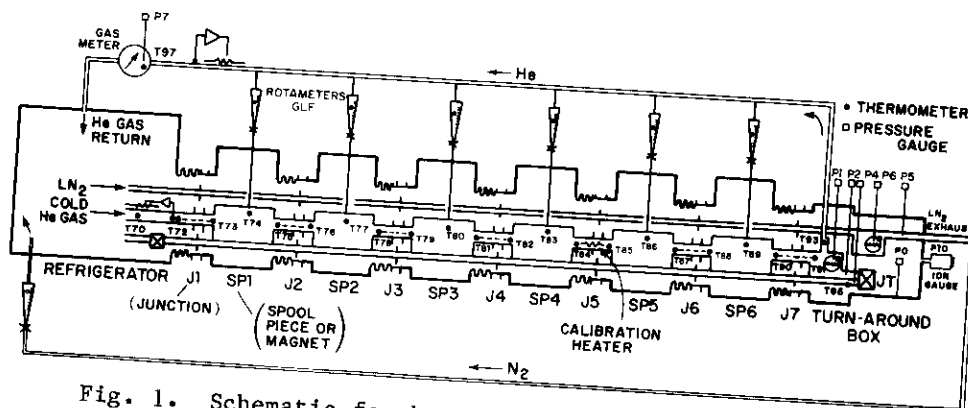

Fig. 1. Schematic for heat load measurements of testing facility, showing train with six spool pieces (SP1-SP6).

calibration.   The insulating vacuum is monitored with an ion gauge,[1] whose logarithmic output is recorded at every interval.

Most of the thermometers are 100 Ω 1/8W carbon resistors[j] specially mounted and calibrated against a carbon-glass[k] unit. The resistors are connected in series with a 10μ A current source whose polarity is computer controlled.   The voltage leads are connected to low signal relay cards[m] in the scanner.

A gas meter[n] actuates a switch for every 0.05 ft^3 of gas. This action is converted into an electronic pulse and these pulses are counted by an S-100 scaler based on an integrated circuit[o]. The application program uses this scaler to calculate the average flow rate between readings.   A thermistor[p] and a pressure trans-ducer at the inlet of the gas meter provide the remaining infor-mation for the calculation of the total mass flow rate.   Part of this flow comes through rotameters from the vapor-cooled leads. This flow is manually set and the reading entered manually into the computer.   A heater and a control system ensure that the temperature of the gas entering the gas meter is close to room temperature.

The application program, written in BASIC[q], is a series of specialized subroutines and several driver programs.   For special monitoring of the system, driver programs can be entered quickly.   Since the program is executed through a BASIC inter-preter, there is no compiling after revisions or additions, making their implementation very fast and easy.   This method of execution is negligibly slower because the revelant time constants of the system are long.   Comments can be easily entered into the recorded data through the terminal.   Day and time are automatically in-cluded in the recorded comment.   At the start of a run, prompting is made for comments identifying the components of the train.

In order to have a simple starting procedure, the master diskette, on the first disk driver, holds the disk operating system, the console processor, the BASIC interpreter and the application program.   The second disk driver has the data diskette containing two files, one storing the data and another the latest values of the application program parameters.   This permits full recovery from application program modifications, power failures, etc.   The full calibration tables for the 30 carbon thermometers are also stored in the master diskette, however, the program stores for each thermometer the interpolation parameters of the last temperature interval used in order to reduce the number of disk accesses.   Special programs, stored in a utilities diskette, can be merged in prior to a run, in order to facilitate changing the calibration tables, since each new run involves new ther-mometers and old ones in new locations.

M. Kuchnir

A conspicuously available listing of the application program, well documented with remarks, an understanding of BASIC by the technicians operating the facility, and a number of lines reserved for their own driver programs are important factors contributing to the utility of this data acquisition system, not only for heat load measurements, but for the general operation of the facility.

HEAT LOAD MEASUREMENTS

For heat load measurements the data acquisition system described above reads the thermometers, pressure gauges and the gas meter at regular time intervals. It processes these data and computes the heat loads between pairs of thermometers for each time interval. A typical scan includes day and time, mass flow rate, 24 temperatures, 13 heat loads, and takes ~ 5 minutes.

The data are valid when the system of components plus refrigerator reaches steady-state. Several steady-states, differing in mass flow rate, power in a calibration heater or lead flow rate (the higher order correction magnets have vapor-cooled leads), are used to verify the consistency of the data.

For the calculation of the heat loads, part of the helium enthalpy table[4] stored in the program is used to interpolate for pressure and temperature. A further correction might be needed when the heat load is largely due to conduction from the N_2 shield, since the value just determined corresponds to a temperature difference from 78 K to the average component temperature during the measurement, which is different from its average temperature in actual operating conditions. Since this conduction in the case of Fermilab superconducting dipoles is mostly through epoxy-fiberglass composites, the expression for the integrated thermal conductivity

$$\frac{\int_{4.6\ K}^{78\ K} \kappa\ dT}{\int_{T_{average}}^{78\ K} \kappa\ dT} = \frac{679.01}{688.88 - T_{average}^{1.5}}$$

based on the data of Kasen[4] is used as a correction factor. This factor usually amounts to less than a 10% correction to the heat load.

The results for one Energy Saver dipole magnet (Serial No. TC-0361) and one Energy Saver quadrupole magnet (Serial No. TQ-D-86) are 9.4 ± 3W and 3.0 ± 3W respectively. About two dozen spool pieces have been measured to date (July 1981) in eight runs.

Their heat load, a function of the lead flow rate, varies from 10 to 18W. The lower value corresponds to the design lead flow rate of 30 scfh.

This capability of taking heat load readings in real-time so to speak has simplified considerably the testing of components for the Fermilab superconducting accelerator.

VENDORS

a. John Fluke Mfg Co., Inc., P.O. Box 43210, Mountlake Terrace, Washington 98043, Model 8502 A.
b. John Fluke Mfg. Co., Inc., Model 2204 A.
c. Cromenco, Inc., 280 Bernardo Ave., Mountain View, California 94043, Model Z2D.
d. Mountain Computer, Inc., 300 Harvey W. Blvd., Santa Cruz, California 95060.
e. Lear Siegler, Inc., Annaheim, California 92804, Model ADM-3.
f. Integral Data Systems, Inc., 14 Tech Circle, Natick, Massachusetts 01760, Model 440.
g. National Semiconductor Co., 2900 Semiconductor Dr., Santa Clara, California 95051, Model L x 16 xx 6.
h. MKS Instruments, Inc., 22-24 Third Ave., Burlington, Massachusetts 01803, Model 310 BHS-10 K.
i. Granville-Phillips Co., Boulder, Colorado 80303.
j. Allen Bradley Co., 1200 S. 2nd St., Milwaukee, Wisconsin 53204.
k. Lake Shore Cryotronics, Inc., 64 E. Walnut St., Westerville, Ohio 43081, Model CGR-1-2000.
m. John Fluke Mfg. Co., Inc. Model 2200A-06.
n. American Meter Co. (Singer), 300 N. Gilbert St., Fullerton, California 92633, Model AL-800.
o. Intel Co., 3065 Bowers Ave., Santa Clara, California 95051, Model 8253.
p. Yellow Springs Instrument Co., Yellow Springs, Ohio 45387, Model YSI-44001
q. Microsoft, 10800 NE Eighth St., Bellevue, Washington 98004.

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